Labrador Sea Water property variations in the northeastern Atlantic Ocean

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[1] Labrador Sea Water (LSW) property variations are analyzed using data from four hydrographic sections occupied along 20°W, from Iceland south toward the equator in 1988, 1993, 1998, and 2003. LSW between the Azores-Biscay Rise and the Rockall Plateau steadily becomes deeper, colder, fresher, denser, and thicker over the 15-year time series. LSW apparent oxygen utilization (AOU) remains unchanged during this time period. The changes analyzed are consistent with previously published spreading rates of 8 years for LSW from the Labrador Sea to 20°W, and emphasize the long reach of decadal LSW variability. **Citation:** Johnson, G. C., J. L. Bullister, and N. Gruber (2005), Labrador Sea Water property variations in the northeastern Atlantic Ocean, *Geophys. Res. Lett.*, *32*, L07602, doi:10.1029/2005GL022404.

1. Introduction

[2] Labrador Sea Water (LSW) is formed by deep convection in the Labrador Sea and its water properties are well documented in the formation region [*Yashayaev et al.*, 2003]. LSW variations have been in large part related to the amplitude and phase of the North Atlantic Oscillation, or NAO [*Dickson et al.*, 1996]. The NAO is an index that reflects fluctuations in the intensities and locations of the high in atmospheric pressure near the Azores and the low near Iceland [*Barnston and Livezey*, 1987]. NAO variations result in large changes in air-sea fluxes of heat, freshwater, and momentum [*Cayan*, 1992; *Hurrell*, 1996; *Visbeck et al.*, 1998] over much of the North Atlantic Ocean, including the Labrador Sea.

[3] LSW properties are set by the depth of convection, along with the temperature and salinity of the mixed layer when it reaches its maximum density in late winter [*Lazier et al.*, 2002]. Since winter conditions are generally harsher (colder, wetter, and windier) over the Labrador Sea during periods of positive NAO, LSW formed during these periods tends to be more extreme (colder, fresher, denser, and thicker). Of interest here is an extended period of high NAO starting in 1989 and continuing through 1995, when LSW formation rates increased, LSW temperatures decreased, and late-winter convection generally reached deeper and deeper from year to year.

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[4] LSW transits the North Atlantic Ocean in a deep western boundary current (DWBC) that is a vital component of the large northward heat flux there [*Hall and Bryden*, 1982]. LSW variations have been traced from the formation site through the DWBC system [*Curry et al.*, 1998; *Molinari et al.*, 1988], with a relatively rapid rate of spreading. In addition, LSW spreads into the eastern North Atlantic via the deep cyclonic subpolar gyre [*Talley and McCartney*, 1982], and LSW property variations there have been used to infer spreading times on the order of years to a decade for LSW from the Labrador Sea around the subpolar gyre [*Sy et al.*, 1997; *Bersch et al.*, 1999; *Koltermann et al.*, 1999].

[5] Here we analyze LSW variability along 20°W sampled by four high-quality full water column meridional hydrographic sections occupied at 5-year intervals between 1988 and 2003. We focus on decadal changes in LSW temperature, salinity, density, potential vorticity (and thickness), and apparent oxygen utilization (AOU).

2. Data

[6] WOCE section A16N is a nominally meridional section that samples the deep eastern basins of the North Atlantic Ocean [http://cchdo.ucsd.edu/]. At least four occupations of the northern portion of this section have been made with relatively closely spaced (55-km or closer unless noted), full water column hydrographic stations with relatively high-quality CTD (conductivity-temperature-depth) data and at least 24 nominal water samples collected per station. The first section analyzed here was occupied in July–August 1988 on the R/V *Oceanus* [*Tsuchiya et al.*, 1992]. The second occupation was in July–August 1993 on the NOAA Ship *Malcom Baldrige* as part of the NOAA OACES program (with 110-km station spacing in most of the subpolar gyre and one 220-km gap between 46°N and 48°N). The third occupation was in April–June 1998 on the RRS *Discovery* [*Smythe-Wright*, 1999]. The fourth occupation was in June–August 2003 on the NOAA Ship *Ronald H. Brown*, as the inaugural cruise of the U.S. Repeat Hydrography Program [http://ushydro.ucsd.edu/].

[7] Full water column CTD temperature and salinity (S) data at 2-dbar pressure (P) intervals are analyzed from all four cruises. Potential temperature referenced to the surface (θ), potential density referenced to 2000 dbar (σ_2), and planetary potential vorticity (Q; the Coriolis parameter divided by the in situ density and multiplied by a locally referenced vertical potential density gradient) were all computed.

[8] The 1988 and 2003 cruises report oxygen data at 2-dbar resolution, but for the 1993 and 1998 cruises, discrete bottle oxygen data were linearly interpolated to this resolu-

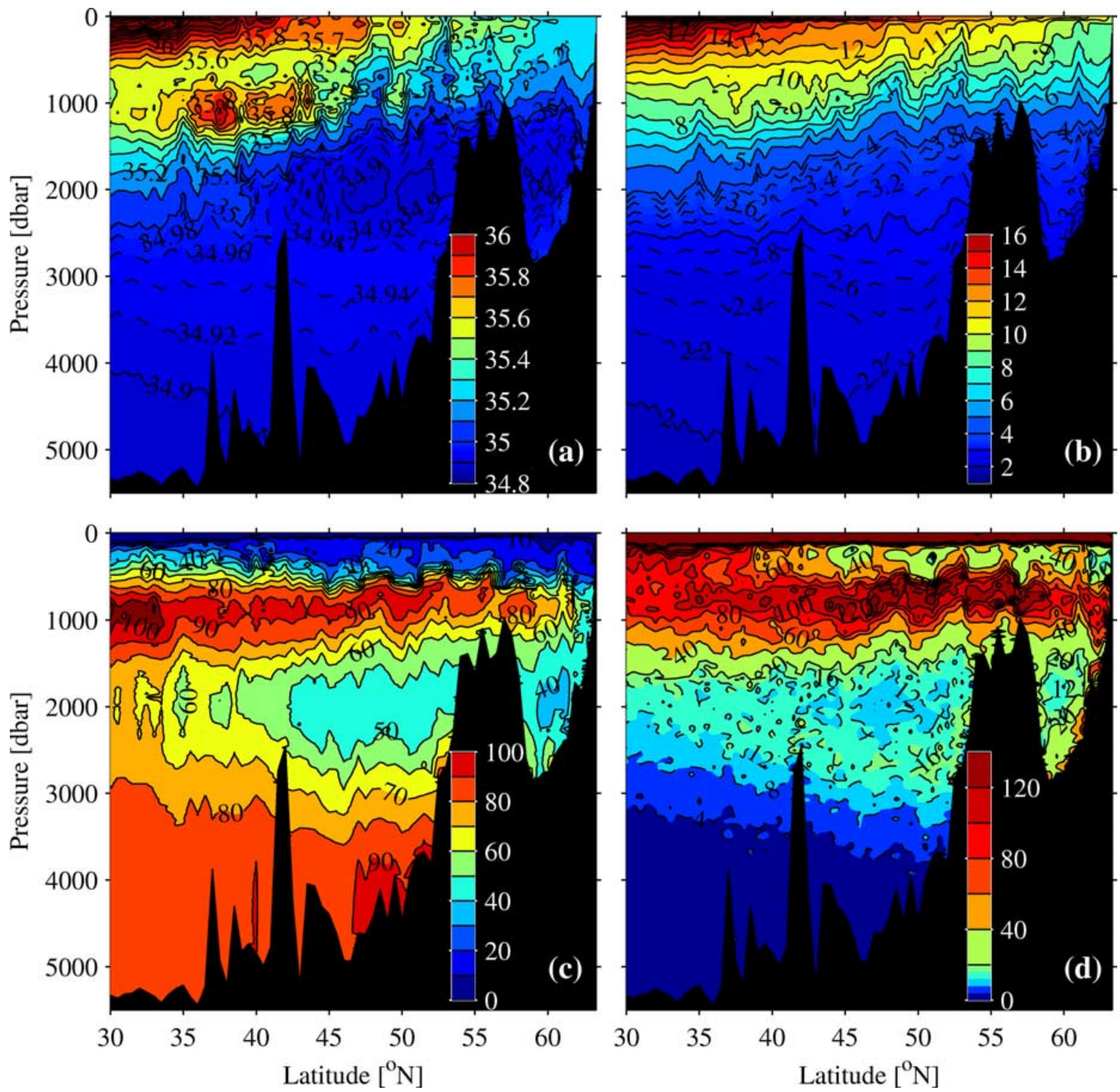

Figure 1. Vertical-meridional sections from a 2003 occupation of a hydrographic section along 20°W of (a) salinity S contoured at 0.1 intervals (solid lines) and 0.02 intervals (dashed lines), (b) potential temperature θ contoured at 1°C intervals (solid lines) and 0.2°C intervals (dashed lines), (c) apparent oxygen utilization AOU contoured at 10 μmol kg^{-1} intervals and (d) Planetary potential vorticity Q contoured at 20 × 10^{-12} m^{-1} s^{-1} intervals (solid lines) and 4 × 10^{-12} m^{-1} s^{-1} intervals (dashed lines).

tion. With 24 bottles per station, the deep oxygen structure is well resolved, and the results presented here are insensitive to interpolation methods. For the 1993 cruise, the bottle oxygen data were multiplied by a factor of 1.02 after consultation with the chief scientist (R. Wanninkhof, personal communication, 2004). After this adjustment, oxygen data from the four cruises agreed to within 3 μmol kg^{-1} in the relatively quiescent and homogenous abyssal subtropical eastern North Atlantic. This range is taken as indicative of the measurement precision among these cruises. AOU was computed by subtracting the measured value from the saturation value computed at θ and P = 0.

[9] Profiles of θ, S, σ_2, and AOU were all low-passed with a 20-dbar half-width Hanning filter, and those of Q with a 80-dbar half-width Hanning filter. The results were then subsampled at 20-dbar intervals for analysis. For isopycnal analyses, the low-passed profile data (now including P) were linearly interpolated to a set of finely spaced σ_2 values.

3. Results

[10] LSW is distinguished along 20°W by a distinct S minimum centered near 2000 dbar from the north edge of the Azores-Biscay Rise (42°N) to off Iceland (63°N), interrupted by the intervening Rockall Plateau around 55°N (Figure 1a). The minimum contrasts strongly with the S maximum of Mediterranean Outflow Water, strongest

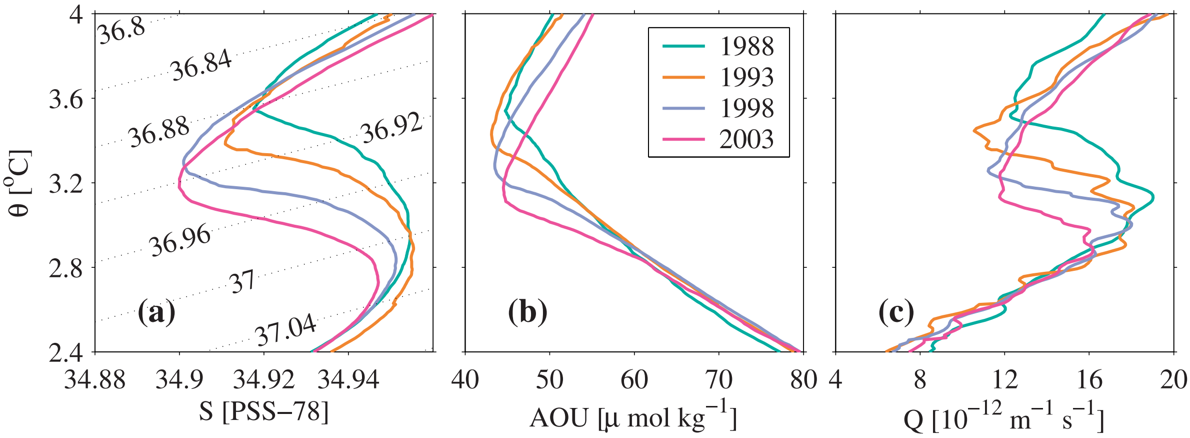

Figure 2. Isopycnally averaged water property diagrams for 43°N–53°N along 20°W using data from repeat hydrographic sections occupied in the years indicated in the legend (a) θ-S with σ_2 [kg m^{-3}] contours (dotted lines), (b) θ-AOU, and (c) θ-Q.

near 38°N and 1200 dbar in this occupation, and more subtly with relatively salty overflow water beneath from the arctic regions. The subtle thermostad in this region around θ = 3.2°C also reflects the LSW convective origins (Figure 1b). Similarly, LSW is associated with an AOU minimum that dips below 50 μmol kg^{-1} south of the Rockall Plateau and below 40 μmol kg^{-1} to the north of that feature (Figure 1c). Finally, LSW exhibits a Q minimum (Figure 1d), again because Q approaches zero in the mixed layer where LSW is formed. When and where LSW is no longer in contact with the surface, Q is a conservative quantity that can be altered only by mixing. Since late winter mixed layers in the Labrador Sea exhibit great thickness, LSW low Q values tend to be persistent.

[11] LSW signatures are strong along 20°W in the Iceland Basin (Figure 1), north of the Rockall Plateau. However, there are only a few stations in the interior of that basin and water-property fields there are variable owing to vigorous overflow and deep boundary currents. The more extensive and less variable LSW signature south of the Rockall Plateau is the focus here.

[12] Hereafter we quantify LSW property changes, monotonic at 5-year resolution, from 1988 through 2003 between the Azores-Biscay Rise and the Rockall Plateau using distance-weighted water property averages along 20°W calculated on σ_2 surfaces (Figures 2 and 3). Station data from 43°N–53°N (inclusive) are used in the averages for the four cruises analyzed. Most cruises occupied 21 stations over this latitude range, except the 1993 cruise, which sampled 10.

[13] In the Labrador Sea, LSW freshens from about 34.89 in 1980 to 34.83 in 1994, a 0.06 change in 14 years [*Yashayaev et al.*, 2003]. At 20°W, the LSW S minimum steadily freshens from just below 34.92 in 1988 to 34.90 in 2003, a 0.02 change in 15 years (Figure 2a). In the Labrador Sea, LSW cools from 3.35°C in 1980 to 2.75°C in 1994, a 0.60°C change in 14 years. At 20°W, θ values at the S minimum cool steadily from about 3.55°C in 1988 to 3.20°C in 2003, a 0.35°C change in 15 years. The inferred 6–11 year lag between LSW freshening and cooling in the Labrador Sea and at 20°W is consistent with other LSW spreading time estimates between these locations [*Koltermann et al.*, 1999]. LSW is both cooler and fresher in the Labrador Sea than at 20°W, with variability reduced by a factor of two in the east. Mixing of LSW with warmer and saltier water while spreading eastward is the likely reason for both the moderation in LSW properties and their variability at 20°W compared with the Labrador Sea.

[14] In the Labrador Sea, LSW σ_2 = 36.89 kg m^{-3} in 1980 and about 36.94 kg m^{-3} in 1994, a 0.05 kg m^{-3} change in 14 years [*Yashayaev et al.*, 2003]. At 20°W, LSW density at the S minimum increases from σ_2 = 36.88 kg m^{-3} in 1988 to 36.93 kg m^{-3} in 2003, a 0.05 kg m^{-3} change in 15 years (Figure 2a). The effect of cooling on LSW density is only partly compensated by that of freshening. The 6–11 year lagged σ_2 values in the two regions agree much more closely than θ and S, with σ_2 of the LSW salinity minimum at 20°W lighter by 0.01 kg m^{-3} than that of LSW in the Labrador Sea but tracking in amplitude variation, consistent with other recent work [*Yashayaev et al.*, 2004]. The much diminished lagged LSW S and θ variability at 20°W compared with that in the Labrador Sea contrasts with the

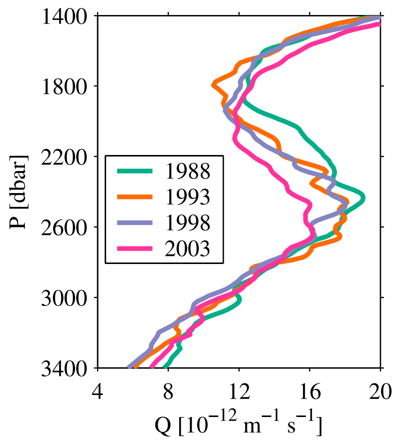

Figure 3. Isopycnally averaged Q vs. pressure for 43°N–53°N along 20°W plotted using data from repeat hydrographic sections occupied in the years indicated in the legend.

almost identical lagged σ_2 variations in both of these locations. These results suggest that LSW properties are modified mostly by isopycnal, as opposed to diapycnal, mixing during eastward spreading.

[15] The LSW AOU minimum at 20°W (Figure 2b) follows that of S, located at the same progressively colder (and denser) values over the 15-year period between 1988 and 2003. Interestingly, mean LSW AOU minima at 20°W do not vary more than 2 μmol kg^{-1} among the four occupations of the section. This variation is within the accuracy of the measurements, and suggests the spreading rates of LSW from the Labrador Sea to 20°W has either remained constant along with the oxygen utilization rates (OUR) or that these two rates have changed in a compensating fashion.

[16] If the spreading time between these two locations were 8 years [*Koltermann et al.*, 1999], and the LSW AOU in the Labrador Sea were near 20 μmol kg^{-1} yr^{-1} [*Clarke and Coote*, 1988], then given roughly 44 μmol kg^{-1} LSW AOU at 20°W, the LSW OUR would be about 3 μmol kg^{-1} yr^{-1}. However, mixing with the higher AOU surrounding waters during spreading will further increase LSW AOU at 20°W, so the OUR estimate made here is really only an upper bound. This estimate is consistent with others of OUR < 3 μmol kg^{-1} yr^{-1} below 500 m [*Sonnerup et al.*, 1999].

[17] At 20°W, the LSW Q minimum (Figure 2c) also tracks those of S and AOU, located at the same progressively colder (and denser) values between 1988 and 2003. The Q minimum amplitude is relatively constant, as might be expected since LSW Q is set to zero upon formation and then increased by mixing processes as it spreads. As is expected from the mixing of a vertical and lateral extrema with surrounding values during spreading, the Q-minimum at 20°W is much higher than that in the Labrador Sea [*Talley and McCartney*, 1982].

[18] At 20°W the LSW Q minimum (Figure 3) deepens slightly and somewhat noisily from near 1800 dbar in 1988 to near 2000 dbar in 2003, as do the other LSW property extrema (not shown). At 20°W the thickness of the layer with $Q < 16 \times 10^{-12}$ m^{-1} s^{-1} increases more steadily from 600 dbar in 1988 to 700 dbar in 1993, 800 dbar in 1998, and 900 dbar in 2003, mostly due to deepening of the lower bounding isovort. This thickening reflects the strengthening of the LSW signal at the source, and the increasing depth to which LSW had been ventilated in the Labrador Sea. The changes in LSW thickness within the Labrador Sea [e.g., *Stramma et al.*, 2004] are much larger than those found at 20°W, although the thickness criteria are different. Again the 6–11 year lag for spreading time and reductions in LSW extrema magnitude and variability by mixing along the way must be factored into the comparison.

4. Discussion

[19] Previous analyses show that LSW in the Labrador Sea became significantly cooler, fresher, denser, deeper, and thicker between around 1980 through 1994 [*Yashayaev et al.*, 2003]. The time-series analyzed here suggests that LSW at 20°W between the Azores-Biscay Rise and the Rockall Plateau showed these same trends from 1988 through 2003. This pattern is consistent with previously published results estimating an 8-year time lag for spreading of LSW signals into the eastern basin [*Koltermann et al.*, 1999].

[20] In addition the LSW S minimum and the co-located θ values are shown to be moderated and their variations attenuated at 20°W compared with analyses in the Labrador Sea. In contrast the LSW AOU minimum value remains effectively constant over 15 years, suggesting uniformity in the 8-year spreading time, with OUR < 3 μmol kg^{-1} yr^{-1}. In addition, while the LSW Q minimum does not change much in amplitude at 20°W, it does deepen and thicken, reflecting changes in the strength of LSW formation. The σ_2 values of LSW property extrema at 20°W closely track LSW σ_2 values in the Labrador Sea, with a 6–11 year lag, reinforcing the importance of isopyncal mixing in moderating the variations in θ and S during LSW spreading.

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